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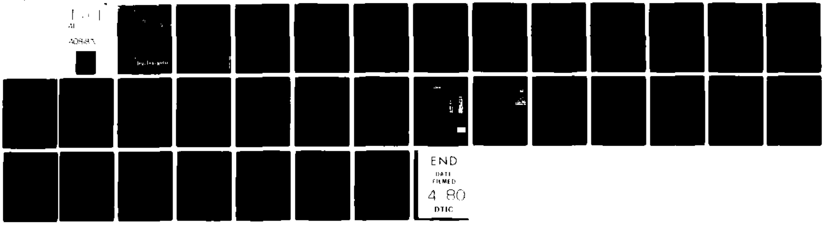

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Final Report On

HIGH POWER SWITCH DEVELOPMENT

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Spark Gap Switch Model

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Studies on the triggering of a high-voltage, gas-insulated spark gap by an electron beam have been conducted. Measurements of the gap voltage, current, and jitter have been made for a wide range of gap conditions and electron-beam cross-sectional areas. The character of the breakdown, for each condition, has been inferred using photographic techniques (streak and open shutter). Current risetimes of approximately 2 ns with subnanosecond jitter have been obtained for 3 cm gaps with gap voltages as low as 50% of the self-breakdown voltage (which can be varied up to 1 MV). The observational time lag, i.e. the

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interval of time between the application of a voltage pulse to the electron gun and the beginning of the current rise in the gap circuit, was 50 ns. The gases used in this series of experiments were: N_2, mixture of N_2 and Ar, and mixture of N_2 and SF_6 at pressures of 1-3 atm. Open shutter photographs show that the discharge is broad in crossection. A number of papers reporting the results obtained in this program have been given at international conferences and two master theses were completed.

Final Report On

HIGH POWER SWITCH DEVELOPMENT

E. Kunhardt and M. Kristiansen

November 29, 1979

Grant No. AFOSR 76-3124
Project Task No. 2301/A7

Research Sponsored by
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RESEARCH OBJECTIVES

1. Investigate fundamental properties of electron beam triggered switches and determine their capabilities and limitations.
2. Investigate breakdown phenomena at high electric field, when the initial space charge in the gap cannot be neglected.
3. Study inductive properties of asymmetric and multichannel discharges, using wires, connected between the electrodes, to simulate the discharge.

I. Introduction

This program was conducted to investigate:

a) the properties of an electron beam triggered spark gap

b) the effects of asymmetry and multichannels on the inductive risetime of a spark gap

In the following sections, we discuss the findings of this study.

II. Electron Beam Triggered Studies

We have investigated the characteristics of an electron beam triggered spark gap. For these investigations, we used the electrodes in an Ion Physics Corp. FX-15 generator made available to us by the AFWL. Considerable modifications were necessary to build a facility suitable for these investigations. This experimental set-up has been described in the previous two annual reports. A diagram of the experiment and its various components also appear in the papers enclosed at the end of this report (Appendix I).

In summary, we have used a 200 keV, .5 kA, pulsed electron beam for the precise switching of high voltages. Using this beam as the source of space charge, we have been able to switch voltages up to 500 kV, ranging from 50 to 90% of self breakdown, in nanosecond time (~ 2.5 ns), with subnanosecond statistics. These results indicate that electron beams can be most desirable in certain very high voltage switching applications.

The various findings of this program have been reported extensively at a number of conferences (1-4). Appendix I gives further experimental details and results.

III. Inductive Properties of Asymmetric and Multichannel Discharges

A test chamber was built [1] to study the effects of asymmetry and multichannels on the inductive risetime of a spark gap. The gap region was formed by an interruption in the center conductor of a constant impedance (50 ohm) coaxial line which is terminated in a matched load. Thin wires were placed between the electrodes to simulate the conduction paths. Using sampling techniques, we have experimentally determined the effects associated with gap spacing, number of channels, channel position, and channel diameter, on the risetime of the current. The results were reported at the 2nd IEEE International Pulsed Power Conference held in Lubbock. The paper, which appeared in the conference proceedings [3], is included at the end of the report (Appendix II). In summary, we found that in the nanosecond regime, variations in the above mentioned parameters have a significant effect on the risetime of the current in the gap circuit. Of particular importance were the difference observed in the risetime due:

1) to the discontinuity in the radial dimension between the electrode and the "spark channel, and
2) to the number of channels.

The best risetimes were obtained when either the radial discontinuity was minimized (i.e. "broad discharge") or when more than one channel was used. Because of the difficulty in achieving multichannel conditions in actual gap breakdown and because the % change in risetime decreases as the number of channel increases, we have concluded that two channels seems to be the most practical. For further details, we refer to Appendix II.

Appendix I

Conference Proceeding Papers - e-beam triggering

Presented at the 2nd IEEE International Pulsed Power Conference
Lubbock, Texas, 1979

AN ELECTRON-BEAM-TRIGGERED SPARK GAP

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Abstract

Studies on the triggering of a high-voltage, gas-insulated spark gap by an electron beam have been conducted. Risetimes of approximately 2.5 ns and subnanosecond jitter have been obtained for 3 cm gaps with gap voltages as low as 50% of the self-breakdown voltage (variable to 1 MV). The switch delay (including the diode) was 50 ns. The working media were N_2, and mixtures of N_2 and Ar, and of N_2 and SF_6 at pressures of 1-3 atm. Open shutter photographs show that the discharge is broad in cross-section.
Voltage, current, and jitter measurements have been made for a wide range of gap conditions and electron-beam parameters. Variations in the character of the discharge have been inferred using streak and open shutter photography. Correlation between electron beam width, beam energy, discharge channel width, current risetime, delay, and jitter are discussed.

Introduction

Several current high priority research efforts such as fusion, the production of high energy-particle beams, and the simulation of environments associated with nuclear weapons detonations, require the generation of very high voltage, high peak power pulses. One of the principle prerequisites to achieving this objective is the development of switches that will allow fast transfer of energy from an energy storage system to the load or transducer. We are currently engaged in a research program designed to improve the physical understanding of switching processes for the subsequent development of an advanced, low inductance, fast rise time, command fired spark gap switch, capable of operating at very high voltages (MV). Encouraging results toward this goal have been achieved by laser triggered switching [1] (LTS), and by e-beam triggered switching [2,3] (EBTS). This paper discusses an investigation into e-beam initiated breakdown which leads to the formation of a volume discharge (proportional to the cross-sectional area of the injected beam), which helps reduce electrode erosion and switch inductance.

The Experimental Arrangement

The experiment consists of an energy storage element, a gas insulated, pressurized spark gap, and a source of energetic electrons. (Fig. 1). The energy storage element and the spark gap are both contained within the high pressure vessel of the Ion Physics Corporation FX-15 (Fig 2). The energy storage element is a Van de Graaff charged co-axial line. It is capable of producing a 1 MV rectangular pulse of approximately 10 ns FWHM duration. The spark gap is formed by an interruption in the center conductor of the line. The stainless steel electrodes have a Bruce profile and are 21.5 cm in diameter. The high pressure in-

Work supported by AFOSR under Grant No. AFOSR-76-3124

sulating gas also serves as the dielectric for the co-axial line. The electron beam is generated by a cold cathode, field emmission vacuum diode, which is located behind the grounded electrode. It is actually placed inside the inner conductor of the output co-axial line, so as to introduce the e-beam axially through a 1" diameter aperature in the center of the electrode. In order to maintain a uniform field distribution in the gap and to protect the foil from the discharge, the aperature was covered with a stainless steel mesh (0.050"). The diode[4] (Fig. 3), designed and built at Texas Tech University, utilizes a spiral groved graphite cathode, and a thin foil anode. Graphite was chosen because of its fast "turn on" properties[5]. The diode was designed to have an impedance of 70 Ω to match that of the driving generator. This generator is a 25 stage modified Marx pulse forming network (Eads pulser)[6]. It combines the voltage multiplicative feature of the standard Marx circuit with the pulse shaping characteristics of a lumped parameter network. The sequence of events in the experiment is as follows: The Marx erects to give an output waveform characterized by a 250 kV trapezoidal pulse of 50 ns FWHM duration with a 4 ns risetime. This pulse propagates down a 70 Ω, oil-filled, co-axial transmission line and appears across the anode-cathode gap of the diode. The diode emits, through a 2 mil. titaminan foil, a 1.5 kA, 200 keV burst of electrons with a 0-50% risetime of 1.5 ns and a duration of 15 ns. This pulsed beam of electrons travels through 1.5 cm of the high pressure gas before it enters the spark gap. The insulating gas is ionized by electron impact, resulting in the subsequent formation of an ionized conduction path and the collapse of the voltage across the gap. The charged co-axial line of the FX-15 discharges, and the resulting wave propagates down a 50 Ω, oil-filled output transmission line, which is terminated in a matching $AlCl_3$ water resistor. The outer conductor of the Marx Generator to diode transmission line also serves as the inner conductor for the FX-15 output transmission line.

Experimental Approach

The characteristics of the spark gap breakdown investigated were: (1) the risetime of the transmitted voltage pulse, (2) the switch delay and jitter, and (3) the spatial character of the breakdown. The diagnostics used were open shutter and streak photography to record the character of the discharge, and a capacitive divider probe (C_1), located in the FX-15 output transmission line, to monitor the voltage pulse generated at breakdown.

The parameters that we varied during the course of our investigation include: (1) The gap polarity (depending on how the Van de Graaff was charged, the target electrode was either positive or negative. When charged positive the injected e-beam was accelerated by the initial electric field in the gap, and for the target electrode negative the beam was decelerated), (2) the gap voltage V_g (V_g was varied between 50% and 98% of the self-breakdown voltage which ranged from 75 kV to 400kV),(3) gas pressure (1-3 atm), (4) the type of gas (N_2, mixtures of N_2 and Ar, and mixtures of N_2 and SF_6), (5) the e-beam diameter (1.25 cm and 2.50 cm), and (6) the e-beam energy (150 keV to 250 keV).

Results

The pulse risetime was observed to vary with the beam energy and ranged from 2.5 to 3 ns. The larger value was obtained for a beam energy of 150 keV and V_g = 100 kV or, 50% $_{VSB}$. The jitter was found to be virtually identical throughout the range of our investigation. Fig. 4a is representative of all jitter measurements. There are 15 separate, superimposed traces of the voltage pulse as monitored by the capacitive probe (C_1), and displayed on a Tektronix 519 oscilloscope. The scope was triggered with the signal from the $\dot{B}$ probe ($\dot{B}_1$) located on the diode transmission line. The sweep speed was 2 ns/div, thus, the resolution is approximately 0.2 ns and the jitter can be seen to be no greater than this amount. These traces correspond to breakdown of a 3.2 cm gap in N_2 at 3 atm. The gap voltage was V_g = 235 kV or 94% V_{SB}. The self-breakdown voltage was 250 kV. The traces in Fig. 4b are further examples of the excellent jitter characteristics. With all other parameters identical to those given above, the beam was

injected when V_g = 130 kV or 52% V_{SB}. Again, the jitter was below the capabilities of our resolution. These two experiments were conducted for positive and negative polarities, yielding identical results. The delay was obtained from figure 5 (a-e), where the $\dot{B}$ signal from the diode transmission line is delayed to appear after the FX-15 voltage pulse. The delay time was measured to be 52 ns in pure N_2, which is consistent with previous studies[3]. The figure also demonstrates that (for these low voltages and pressures) the delay was invariant to both the pressure and the gap voltage (as a function of the self-breakdown voltage). We should also note that these results were obtained with a DC charged gap; one would expect the performance to be better for a pulse charged gap.

The character of the gas discharge for e-beam initiated breakdown was determined from open shutter photographs. This is shown in Fig. 6a when the target electrode was charged positive and in Fig 6b for a negative charged electrode. These two photographs are representative of the spatial character of the discharges observed throughout the range of our investigation. For the same polarity, the light intensity varied as we changed experimental characteristics. For different polarities, the character of the light emission are different, indicating that there is probably a difference in the breakdown processes. Note that for both cases, the breakdown takes the form of a volume discharge. No localized spark channels were seen.

Fig. 7 demonstrates the variation of the discharge as a function of the e-beam diameter. Note that the volume of the discharge is proportional to the cross-sectional area of the injected beam.

Fig. 8 depicts the variation in the dimensions of the discharge cross-section as a function of the energy of the injected beam. The light intensity is seen to be significantly increased when a more energetic beam is introduced into the gap. To investigate the significance of this observation, voltage pulses for varying e-beam energy were recorded (Fig. 9). The amplitude of the pulse is also observed to be a function of the beam energy. These results indicate that the degree of ionization in the discharge plasma, hence the resistivity varies with the beam energy. The voltage drop across the gap is, therefore, a function of the e-beam energy.

Streak photographs of the discharge are shown in Fig. 10. Again, we can observe a difference between the cases of positive and negative target electrodes in the gap. Preliminary analysis indicate that the early emission of light corresponds to the actual breakdown (the time duration is the same as the voltage pulse), and the second emission is the result of the recombination process. Further analysis of these observations are presently being made.

Conclusions

The results obtained in this series of experiments on e-beam triggered switching are summarized as follows: (1) fast risetime (2.5 ns). (2) low jitter (less than 0.2 ns for $V_g \geq 50\%\ V_{SB}$), and (3) volume discharge. The characteristics make e-beam triggered switches highly desirable for many applications.

The risetimes of the self-breakdown and the triggered voltage pulses were virtually identical, as demonstrated by the superimposed traces shown in figure 11. This is due to the fact that the pulse risetimes were generator limited rather than spark gap limited.

The demonstrated low jitter (particularly when operated at voltages well below the self-breakdown voltage), is one of the most significant contributions of this work. Small jitter is crucial to the successful operation of any pulse power system, however, it becomes extremely critical in any scheme that utilizes the simultaneous discharge of parallel pulse forming lines into a common load. Prefires can be virtually eliminated, due to the ability of the switch to function reliability at low voltage levels. The diode and, therefore, the switch has a very good single shot reliability, which eliminates most misfires.

The EBTS breakdown was observed to take the form of a volume discharge (proportional to the size of

the injected beam). This large area breakdown offers several advantages over the narrow channel breakdown found with most switches (e.g. LTS). These are: (1) The EBTS can be scaled up to very large area electrodes and transmission lines while maintaining a low switch inductance (a particularily attractive concept is an annular geometry), whereas other switches cannot duplicate this, unless multiple, current-sharing channels are formed. This, however, is not easily accomplished. In LTS, for example, multiple channels can be triggered by geometrical beam spliting[1], but this method has optical alignment and maintenance problems particularly on large systems. This problem however, can probably be circumvented by the use of fiber optics[7]. (2) The volume discharge should result in a substantial lowering of the switch inductance[4], hence, faster risetimes. (3) The volume discharge minimizes electrode erosion, thereby enhancing the switch lifetime and thus promoting the possibility of developing a reliable rep-rated EBTS. The recovery time should also be reduced as contrasted to the narrow channel discharge case because of the lower degree of ionization per unit volume.

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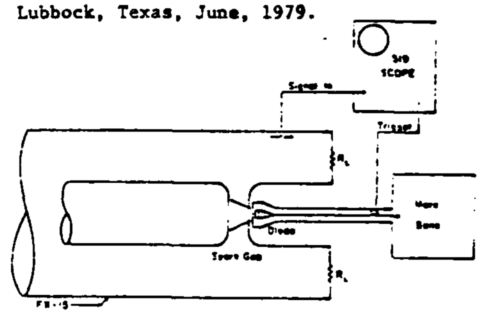


Figure 1: Basic Arrangement

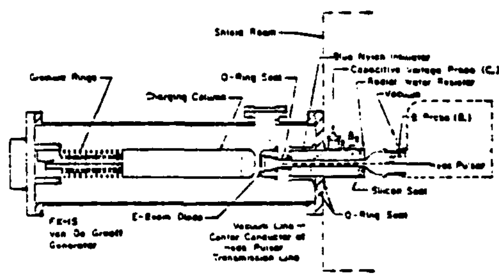


Figure 2: Experimental Arrangement

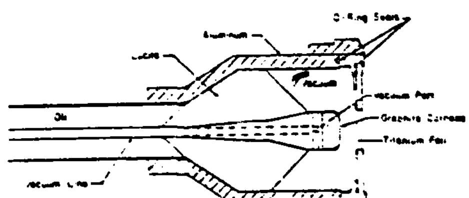


Figure 3: The Diode

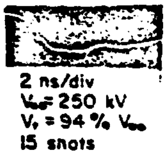


Figure 4a

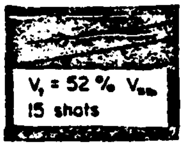


Figure 4b

Fig. 4 Jitter

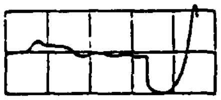


Figure 5: Delay

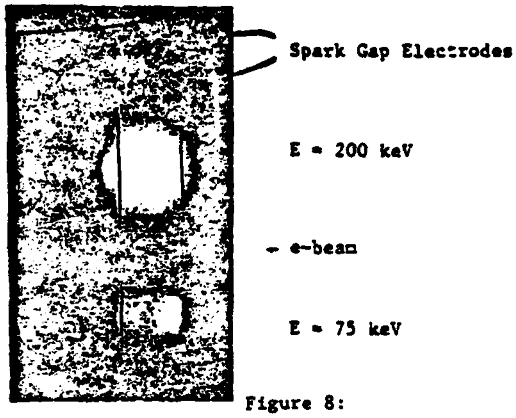


Figure 8:

Variation in the open shutter photographs of the discharge as a function of the e-beam energy

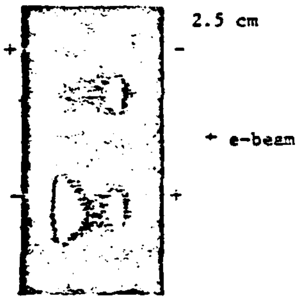
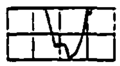
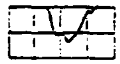


Figure 6:
Variation is the open shutter photographs of the discharge as a function of the polarity of the target electrode



E_p = 200 keV



E_p = 80 keV

Figure 9·
Pulse Amplitude as a Function of the E-Beam Energy

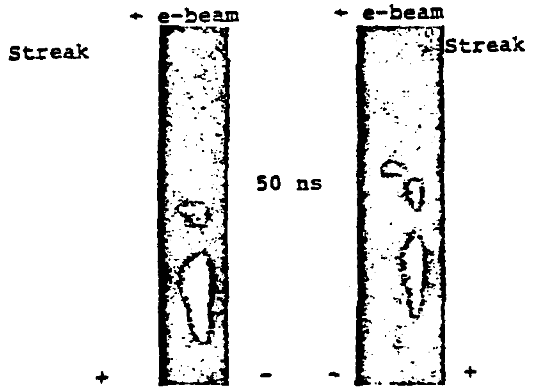


Figure 10a
Positive Case

Figure 10b
Negative Case

Fig. 10
Streak Photographs of E-Beam Initiated Breakdown

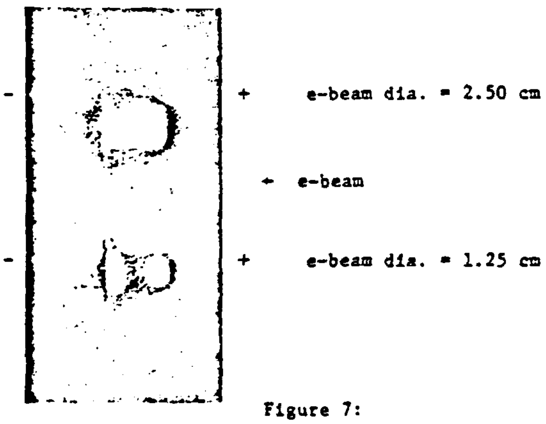


Figure 7:
Variation in the open shutter photographs of the discharge as a function of the e-beam cross-sectional area

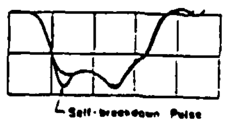


Figure 11:

Superimposed self-breakdown and e-beam initiated breakdown voltage pulses

Abstract submitted for the
1979 IEEE INTERNATIONAL CONFERENCE ON PLASMA SCIENCE
June 4-6, 1979
Montreal, Canada

Electron Beam Initiated Spark Gap Breakdown.

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Several of the current high priority research efforts such as fusion, the production of high current charged particle beams, and the simulation of electromagnetic radiation produced by nuclear explosions, require the generation of very high voltage, high energy pulses. One of the principal prerequisites to attain this objective is the development of a switching device that will allow fast transfer of energy from an energy storage device to the load. The Plasma and Switching Laboratory of the Texas Tech Electrical Engineering Department is currently engaged in experiments designed to provide the physical understanding for the subsequent development of an advanced, low inductance, fast risetime. spark gap switch, operating at very high voltages (Megavolts). When a high voltage is applied to a spark gap filled with a gas at a given pressure, the transition from insulating gas to a highly conducting arc may proceed via different physical processes depending upon the initial conditions existing in the gap and the characteristics of the applied voltage. Traditionally, UV irradiation of the cathode has been used to control the initial space charge in the gap. As alternative methods, the use of Lasers (1) and Electron beams (2) have been studied.

In this paper, we report voltage-current and photographic results obtained on a facility designed to investigate the breakdown of a spark gap due to the injection of an energetic electron beam. We have the capability of applying up to 1 MV to gaps pressurized to 15 atmospheres. The experimental set up consists of three main units: 1) the gap, 2) the electron gun, and 3) the diagnostics. For the gap, we use the electrodes of an FX-15 generator (Ion Physics Corporation). The electron gun, designed and built at Tech has the following characteristics: Electron Energy: 200 kV, Beam current: 500 A, Pulse width: 15 ns, Pulse risetime: 4 ns, Beam radius· 1.25 cm. Different values from those listed have been obtained using different kinds of cathode configurations and applied voltages. Current-voltage measurements using a Tektronix 519 Oscilloscope and a fast streak camera (.1 ns resolution) are at present the main diagnostics. One of the main problems encountered in the design and construction of this facility for operation at very high voltages was the introduction of the electron beam into the gap, while keeping uniform impedance conditions throughout the system. How this constraint was met in the overall design of the system will be briefly discussed.

The mechanics of the experiments done are as follows: with the FX-15 charged to 60%-90% of the self breakdown voltage, the electron beam is axially introduced into the gap through a hole made on the cathode, causing the collapse of the voltage across the gap. A voltage divider is used to monitor the gap current during breakdown. Streak photographs with the entrance slit normal and along the discharge axis have been taken. Typically, current risetimes of ~ 4 ns have been obtained with a 3.175 cm gap pressurized to 30 psi of nitrogen A relatively wide channel is observed. The width of the channel corresponds to the width of the electron beam. Correlation between beam width, channel width, and current risetime will be discussed.

* Work supported by AFOSR under Grant # AFOSR 76-3124

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Presented at the 3rd International Topical Conference on High Power Electron and Ion Beam Research and Technology, Novosibirsk, USSR, 1979

APPLICATIONS OF ELECTRON BEAMS FOR PRECISE SWITCHING OF HIGH VOLTAGES *

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ABSTRACT

An advanced, externally triggered, spark gap switch, capable of closing in a few nanoseconds, with subnanosecond statistics, is being developed. One of the principal parameters that determines the characteristics of a spark gap switch is the nature of the space charge produced in the gap by the triggering mechanism. In this paper, we describe the application of a 200 keV, .5 kA, pulsed electron beam for precise switching of high voltages. Using this beam as the source of space charge, we have been able to switch voltages up to 500 kV with nanosecond statistics. The characteristic of the electron gun, the experimental switching arrangement, the results obtained with this arrangement, and the desirable characteristics of this switching technique are discussed.

1. INTRODUCTION

Precise high power switching has branched into two main areas of concentration. These areas are laser triggering [1] and electron-beam triggering [2,3,4]. The switching characteristics of these methods are determined primarily by the nature of the space charge produced in the gap.

* Work supported by AFOSR under Grant No. AFOSR-76-3124

This paper describes electron-beam switching experiments conducted at Texas Tech University's Switching Laboratory. An electron beam gun was designed and constructed to meet special requirements for the experiment. The e-beam was characterized and used to precisely trigger a spark gap. Investigation into switch risetimes and jitter are discussed. The broad discharge channels of e-beam triggering were also investigated.

2. ELECTRON-BEAM GUN

The electron beam is generated by a cold-cathode, field-emission, vacuum diode. The diode must be 70 Ω to match the generator and it must also be able to withstand 3 atmospheres of external pressure. In addition, an electron beam current of at least 500 amps is desired. With these constraints, the diode shown in Fig. 1 was designed and constructed to generate the e-beam for these experiments.

The cathode is a cylindrical piece of dense graphite that is screwed onto the terminating section of the aluminum, oil-insulated, diode transmission line. Lucite is used to support and insulate the transmission line and the cathode. The exposed surfaces of the lucite are cut at 45° angles to minimize the probability of surface flashover. In order to minimize damage to the lucite in the event of flashover, diffusion pump oil is lightly spread on all interior diode surfaces except the cathode and anode.

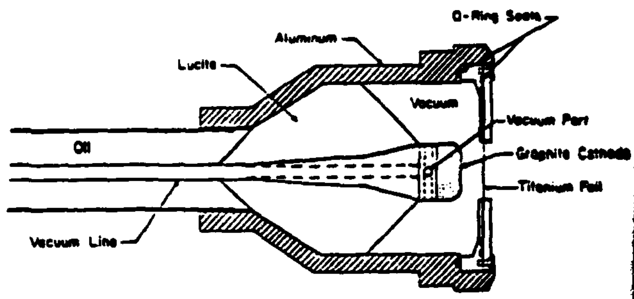

Fig. 1 E-Beam Diode

The anode is made of 2 mil titanium foil. Titanium is used because of its excellent strength characteristics. Two mil thick foil is needed in order for the 2.5 cm diameter beam window to withstand at least 3 atmospheres of pressure. A vacuum of approximately 10^{-5} torr is maintained inside the diode during operation. The vacuum line passes through the center conductor of the diode transmission line.

To generate the e-beam a 50 ns, 4 ns risetime 200-250 kV pulse is applied to the diode via the diode transmission line. The pulse unit used to generate the e-beam is shown in Fig. 2. This unit is composed of 25 pulse-forming modules that are triggered like a Marx

bank.

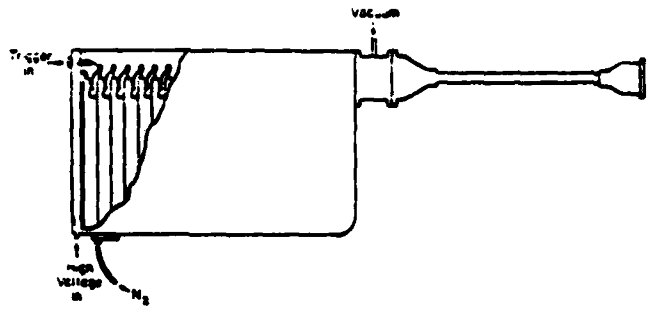

Fig. 2 E-Beam Gun

3. E-BEAM DIAGNOSTICS

The e-beam current was measured using a Faraday cup collector and a self-integrating Rogowski coil [5] (Fig. 3). A beam current of .5 kA with a 1.5 ns risetime and a 15 ns duration was measured.

A time-integrated radial profile of the beam was obtained using photographic techniques. The recording medium, Kodak SO-343 thick base film, was placed directly in front of the foil window and enclosed in a vacuum. Exposure of the film was due only to electron impact, thus an accurate profile of the e-beam was obtained. The developed film was scanned with a densitometer to get the intensity profile of the beam. This profile is shown in Fig. 4.

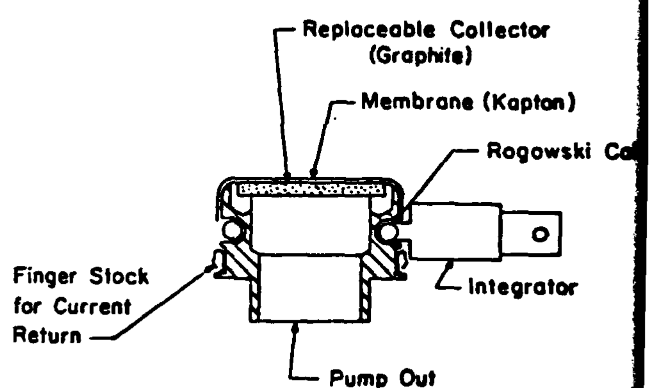

Fig. 3 Faraday Cup Assembly

The e-beam energy was theoretically approximated to be 100 keV. This approximation is based on the energy transmission coefficient for 2 mil titanium foil as calculated by Seltzer and Berger [6]. According to their calculations, 73.5% of the energy of a 200 keV beam is absorbed by the foil, and about 26.5% of the energy of a 300 keV beam is absorbed by the foil.

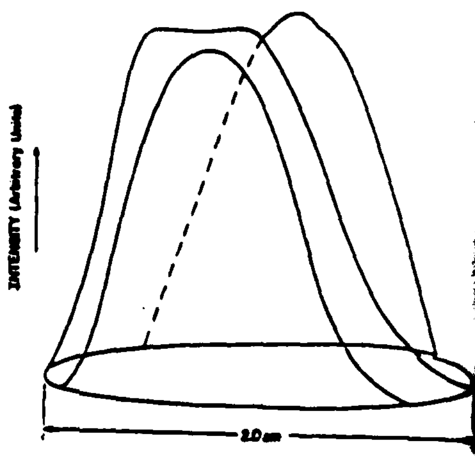

Fig. 4
Beam Intensity Profile

4. SWITCHING EXPERIMENT

The switching experiment requires coaxial symmetry in order to study the characteristics of the switch with minimal influence from the external circuit. The complete experimental arrangement is shown in Fig. 5. The van de Graaff generator on the left in Fig. 5 charges

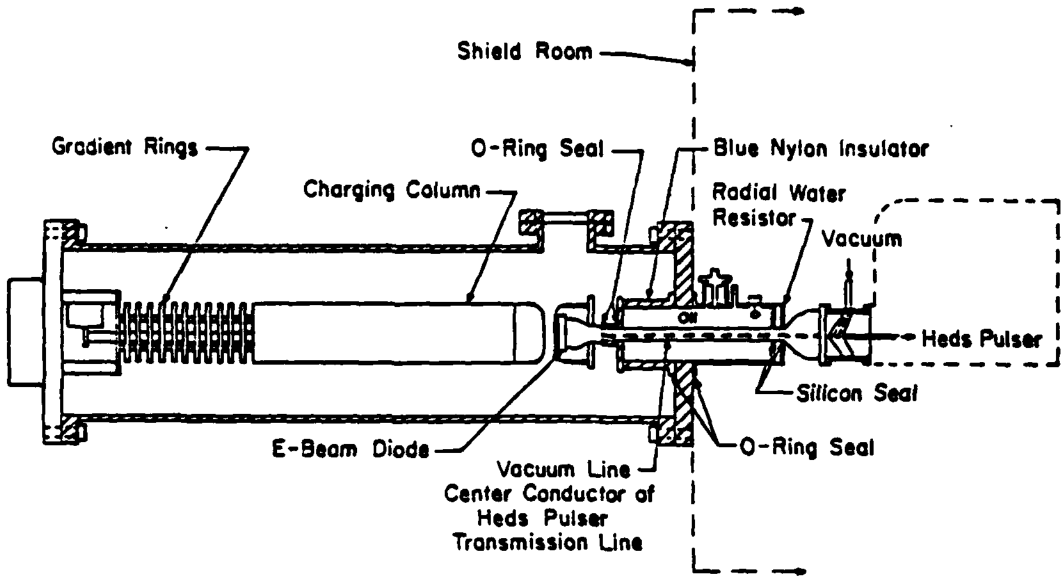

Fig. 5 Experimental Arrangement

a 50 Ω co-axial transmission line. The electron beam is fired into the gap along the axis. The line pulse propagates down a 50 Ω, oil filled transmission line, to a 50 Ω matched water resistor. Diagnostic probes, including a capacitive voltage divider and a $\dot{B}$ probe located in this transmission line are used to measure switch rise-times and jitter.

5. EXPERIMENTAL RESULTS

Open shutter photographs of the e-beam initiated breakdown showed the breakdown channel as being broad and diffuse (approximately one order of magnitude larger in diameter than for self breakdown) for gap voltages of 50-90% of the self-breakdown in N_2 at gap voltages up to 250 kV. The diffuse channel occurred for both the case where the e-beam is accelerated by the electric field in the gap ("positive case") and where it is decelerated by the field ("negative case"). A significant difference in the discharge channel between these two cases can be seen (see Fig. 6a & 6b).

the positive case, the breakdown channel became filamentary. The same thing occured for voltages above ~ 320 kV in the negative case. The filamentary channels (see Fig. 9) were accompanied by increased jitter in the switch. This occurence seems to be partly dependent on the electron beam energy.

Fig. 9
Filamentary Channel

The effect of e-beam energy on the breakdown can be seen in Figs. 10a and 10b. In Fig. 10a the e-beam diode voltage was 220 kV. Fig. 10b shows a decrease in the voltage pulse amplitude due to a lower e-beam energy. (Diode voltage-160 kV)

a

b

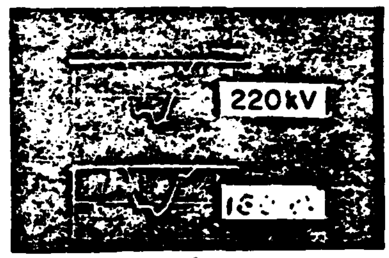

Fig. 10
Variation due to change in E-Beam Energy

6. CONCLUSIONS

Electron beam triggering has been shown to provide precise high power switching. It has the desirable characteristics of fast risetimes (low inductance) and subnanosecond jitter for gaps charged from 50 to 90% of self breakdown. The broad diffuse channel occurring with e-beam triggering has the effects of lowering the rate of electrode erosion and reducing the channel inductance by about 1/2.

Total beam energy seems to be an important quantity in maintaining the broad channel during breakdown. Increasing the beam-energy may also result in the formation of broad channels at higher gap voltages.

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Appendix II

Conference Proceedings Paper - simulations

Presented at the 2nd IEEE International Pulsed Power Conference, Lubbock, Texas, 1979

20

SIMULATION OF INDUCTIVE AND ELECTROMAGNETIC EFFECTS ASSOCIATED WITH SINGLE AND MULTICHANNEL TRIGGERED SPARK GAPS

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Abstract

When breakdown of a pressurized spark gap is initiated by a high power laser, a narrow spark channel is quickly established. In this case, the risetime of the current in the external circuit due to the breakdown of the gap is determined in a large measure by the properties of this spark channel. To study the inductive and electromagnetic effects associated with the channel dimensions and the resulting physical discontinuities, experiments have been conducted using spark gaps where the discharge channel is simulated by a very thin wire. Current risetime measurements for various wire sizes (i.e., spark channel radius), wire position (i.e., on or off axis), and number of wires (i.e., multichanneling) have been carried out. The risetime values thus obtained agree quite well with the laser-triggered, single and multichannel, spark gap results. These results can be qualitatively explained using simple inductive circuits which dramatically underline the inductive character of the breakdown. The significance of these results in revealing the mechanism of spark gap breakdown will be discussed.

As current risetimes in sparkgap switches approach nanoseconds, it becomes increasingly important to understand the electromagnetic effects that are associated with the geometry of the sparkgap and arc channel. This is particularly important in the case of high impedance, triggered systems where the effects of the resistive phase of breakdown are not important. For example, Guenther and Bettis [1] conducted experiments using a 50 ohm, laser triggered system where the risetime was determined almost exclusively by the inductive phase. In this case, those electromagnetic effects, associated with the dimensions of the electrode and the arc channel, can be investigated by simulating the channel with thin wires.

The experimental arrangement, shown in Fig. 1, was used to simulate a high impedance system for the investigation of these aforementioned electromagnetic effects. The gap region was formed by an interruption in the center conductor of a constant impedance (50 ohm) coaxial line which is terminated in a matched load. Thin wires are placed across the gap to simulate the conduction paths.

The simulation arrangement may be thought of as a set of three cascaded transmission lines (shown in center of Fig. 2) with the gap section, in this case, having a very high characteristic impedance. Because of this, and for the purpose of calculating risetimes, the system may be modeled by the inductive circuit shown at the bottom of Fig. 2. In this circuit, the inductance is given by [2]:

$$L = \frac{60\ell}{c} \ln(b/a) \qquad (1)$$

where a and b are the diameters of the wire and outer conductor of the transmission line respectively; c is the speed of light in meters per second, and ℓ is the gap distance in meters. Since transmission line techniques do not account for the three dimensionality of the problem, this circuit model is useful for determining the current risetime only to a first approximation. Because of boundary conditions, the transverse electric field must be zero at the discontinuities occuring at the electrode-channel junctions. Higher order modes are created here to satisfy these boundary conditions, while still allowing for the propagation of the current pulse through the gap [3]. If these modes are evanescent and non-interactive, it is possible to modify the transmission line and circuit models by placing capacitors at each discontinuity [3] and at each end of the inductor, respectively. Some of these higher order modes do

propagate, however, and in general will, making this modified model unacceptable for the accurate determination of current or voltage risetime.

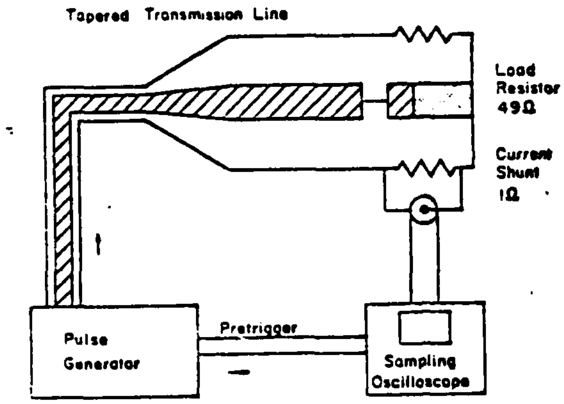

Fig. 1 Experimental Arrangement

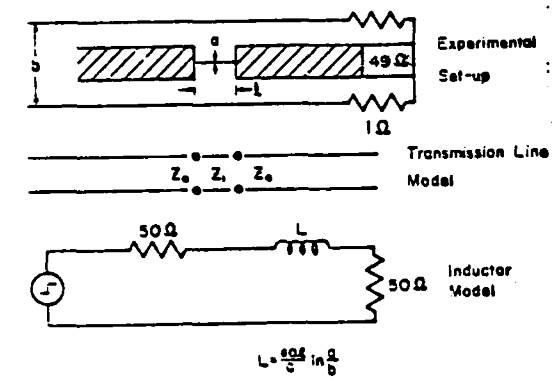

Fig. 2

Using sampling techniques and the setup in Fig. 1, we have experimentally determined the geometrical effects associated with gap spacing, number of channels, channel position, and channel diameter on the risetime of an incident voltage pulse (Fig. 3). The experimental risetimes were determined using the relation:

$$\tau_e^2 = \tau_o^2 - \tau_i^2 \qquad (2)$$

where $\tau_o \equiv$ observed risetime

$\tau_i \equiv$ risetime of incident pulse

We have compared these results with risetimes calculated from the circuit model at the bottom of Fig. 2 with the risetime given by:

$$\tau_R = 2.2 \frac{L}{2Z_o} \qquad (3)$$

A graph of the risetime (after being corrected for the finite bandwidth of the current shunt and incident pulse) versus gap distance is shown in Fig. 4. The risetime of the transmitted pulse decreases as gap distance decreases in both the experimental case and the case when the risetime is determined from equation 3. This is explained by the fact the inductance of the channel and, therefore, the associated time constant decrease with decreasing gap distance. One should also note that while the relative difference between the calculated and experimental risetime remains fairly constant, the percentage difference actually increases as the gap distance is decreased from 3.8 cm. This may be explained by the fact that the high order modes, created at each discontinuity, interact more with each other as the spacing decreases, and this interaction tends to have an increasing effect on risetime. Note, however, that as gap distance is reduced further still, from 2 cm, the capacitance of the gap plays a greater but opposite role, causing the percentage difference between the calculated and experimentally determined risetimes to decrease (see Fig. 4).

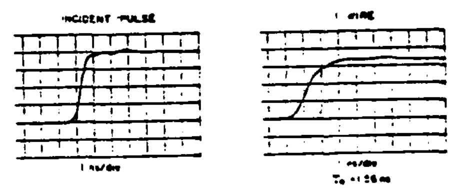

Fig. 3

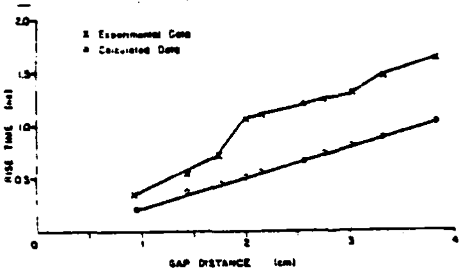

Fig. 4

The geometrical effects associated with multichannel discharges were simulated by placing various number of wires at different positions in the gap. Since the characteristic inductance of the gap section decreases with increasing numbers of wires, it is expected that the risetime should

decrease also. This decrease is particularly acute between rise times associated with one and two wire channels (see Figs. 5 and 7).

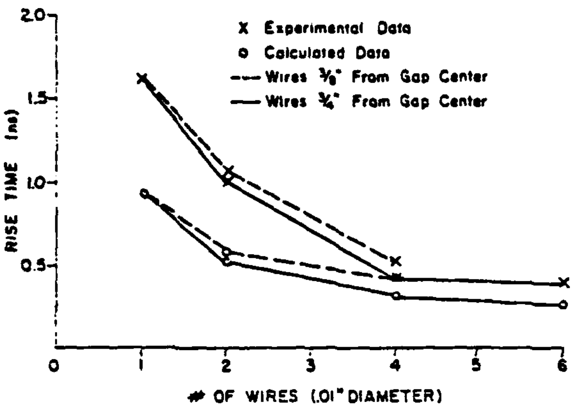

Fig. 5

As the number of wires increases, the electromagnetic field distribution more accurately approximates that of a larger diameter wire. It then follows that large numbers of wires placed at the edge of the gap have an associated risetime that is smaller than the case when the same number of wires are placed closer to the axis of the gap since the associated inductance of the "effective" large diameter channel is smaller. Similarly it follows that the experimental risetime should more closely match the rise time calculated from equation 3 since the "effective" large diameter wire produces less of a discontinuity to the transverse electromagnetic fields of the incident pulse, than the smaller "effective" diameter wire. This is verified by the graph in Fig. 5.

Finally the effects of channel thickness on risetime were determined by varying the diameter of the wires used to simulate the channel. Again, since the characteristic inductance of the gap section associated with the thicker wires is less than that associated with thinner wires, it is expected that risetimes should also be less. This is shown in the plot of risetime versus channel diameter in Fig. 6. Note that the difference between calculated and experimentally determined risetimes tends to become smaller as the thickness of the channel is increased. This decrease is due to two reasons. First, less high order modes are generated in the gap section when thicker wires are used, hence shorter risetimes for the experimental case. Secondly, as wire thickness begins to approach the diameter of the center conductor of the main line, we no longer have the necessary condition that the impedance of the gap be much greater than the impedance of the main line rendering the risetimes calculated from the inductor model too large for the very large diameter wires that we tested.

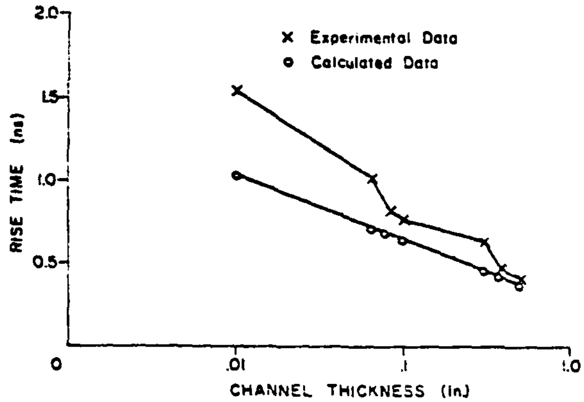

Fig. 6

The importance of these effects in high impedance triggered systems, may be further ascertained by comparing the results obtained in our simulation with the data obtained by Guenther and Bettis [1] using the laser trigger system mentioned previously. They studied the risetime of single and dual channel sparkgaps triggered by one or two laser beams focused on the cathode. A risetime of 2 ns for a single channel and 1.12 ns for dual channels were obtained in their experiment. This is a 44% difference between the two cases. Figure 7 shows a comparison between photographs of oscilloscope traces when one and two .01 inch diameter wires are used to simulate the arc channels. We have a 34% difference between the risetimes of the single and dual wire cases. Considering that the discontinuities in their experiment are more abrupt, (i.e. the cutoff frequency for the higher order modes in their experiment was 200 MHz, whereas in ours it was 600 A), the results compared

favorable. Moreover, note that the increase in the risetime for the single channel case is consistent with our explanation.

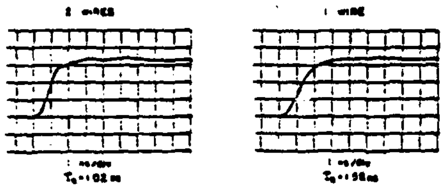

Fig. 7

It is apparent from these results that in nanosecond regimes, current risetime is strongly dependent on the geometry of the spark gap and arc channel system. If minimization of current risetime is to be achieved, reduction in the electromagnetic discontinuities must be considered. One way to accomplish this is by multichannelling. From our results, the most desirable condition, for this case, is the simultaneous creation of either two or four channels at the outer edges of the spark gap. Considering the problems of simultaneously producing four channels, it seems that the percentage reduction using two channels may render this case to be the most practical.

Work supported by AFOSR under Grant #AFOSR-76-3124.

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SWITCHING LAB PERSONNEL:

1. Dr. M. Kristiansen: Horn Professor, Principal Investigator
2. Dr. E.E. Kunhardt: Assistant Professor, Co-Principal Investigator
3. Dr. M.O. Hagler: Professor, Research Faculty Member
4. K. McDonald: Graduate Student, M.S. Candidate
5. M. Newton: Graduate Student, M.S. Candidate
6. G. Wood: Graduate Student, M.S. Candidate

Publications:

1. Submitted for publication to Physical Review:

   Development of Electrical Breakdown in Dense Gases, E.E. Kunhardt and W.W. Byszewski.

2. In preparation:

   Electron Beam Initiated Breakdown of a Gas in a Spark Gap, E.E. Kunhardt, K. McDonald, M. Newton, M. Kristiansen, and A. Guenther.

Conference Papers:

1. "Electron Beam Initiated Spark Gap Breakdown", 1979 IEEE International Conference on Plasma Science, Montreal, Quebec, Canada, June 4-6, 1979, K. McDonald, M. Newton, E.E. Kunhardt M. Kristiansen and M.O. Hagler.
2. "Simulation of Inductive and Electromagnetic Effects Associated with Single and Multichannel Triggered Spark Gaps", 2nd IEEE International Pulsed Power Conference, Lubbock, Texas, June 12-14, 1979, S. Levinson, E.E. Kunhardt, M. Kristiansen, and A.H. Guenther.
3. "An Electron-Beam-Triggered Spark Gap', 2nd IEEE International Pulsed Power Conference, Lubbock, Texas, June 12-14, 1979, K. McDonald, M. Newton, E.E. Kunhardt M. Kristiansen, and A.H. Guenther.
4. "Applications of Electron Beams for Precise Switching of High Voltages",3rd International Topical Conference on High Power Electron and Ion Beam Research and Technology, Novosibirsk, USSR, July 3-6, 1979, M. Newton, K. McDonald, E.E. Kunhardt, M. Kristiansen, and A.H. Guenther.

Thesis Completed:

1. K. McDonald, M.S. Thesis:

   "An Electron Beam Triggered Spark Gap"

2. M. Newton, M.S. Thesis:

   "Investigation of Electron Beam Initiation of Spark Gap Breakdown".

INTERACTIONS

Consultative and advisory functions to other laboratories, agencies, etc:

(1) M. Kristiansen served as Co-Chairman of the Pulsed Power Summer Study for the National Academy of Sciences, Air Force Study Board at Kirtland AFB on July 11 to August 5, 1977. The report preparation phase of this study is still in progress and Dr. Kristiansen participated in the briefing to the AF Study Board at Edwards AFB on November 18, 1977. (In attendance: Generals Allen, Hendricks and Stafford).

(2) During this grant, we have received on loan from the AFWL much valuable equipment (e.g. two lasers and an interferometer). In a small reciprocal process, we lent the Applied Physics Branch at the AFWL 18 energy storage capacitors on July 17, 1977.

(3) Numerous visits by our people have been made to the AFWL and Dr. Guenther of the AFWL has visited us several times during the grant period. During these visits various technical matters related to the work on this grant were discussed.

(4) Dr's. Kristiansen (TTU) and Guenther (AFWL) also serve together on the organizing committee of several national and international conferences related to pulsed power technology, (13th and 14th Modulator Symposium, 2nd International Pulsed Power Conference, International Symposium on Discharges and Electrical Insulation in Vacuum) and co-authored a paper on Switching Requirements for Fusion Reactors which was presented at the N.C. Christophilos International Summer School and Conference on Plasma Physics at the Island of Spetse, Greece, on July 20-30, 1977.

(5) Dr's. Kunhardt (TTU) and Guenther (AFWL) are co-authoring a paper on spark gap triggering which will be submitted for publication in Journal of Applied Physics.

(6) Dr's. Kunhardt (TTU) and Kristiansen (TTU) (2-18-77 and 9-22-77) visited the Physics Directorate of AFOSR and discussed the research progress with Capt. Gullickson and other AFOSR staff members.

(7) We have held very brief and preliminary discussions with Dr. F. Rose of the NSWC at Dahlgren, Virginia, regarding a possible cooperative study based on some of our theoretical studies of sparkgap breakdown and their experimental investigations of self-triggered gaps.

(8) We have discussed the design of our electron beam trigger gun with Dr. Parker of ONR who also provided us the needed graphite block for the electrode.

(9) Dr. Kristiansen served as a consultant to Palisades Inst. on their DARPA Contract MDA903-76-C-0253, "Technical Assessment Recommendation Panels". He served with Ian Smith of Physics International Co. and Ihor Vitkovitsky of ONR on the subpanel on Pulsed Power Energy Storage and Switching.

(10) Dr. Kristiansen was a member of a DOD Study Group which assessed the European State-of-the-Art in pulsed power during the Summer of 1978. Principal DOD participants: A. Guenther, AFWL; R. Verga, AFAOL; F. Rose, NSWC. The final report of this study is being prepared.

(11) Dr. Kristiansen has been intimately involved with the organization of several DOD sponsored conferences, including:
The First IEEE International Pulsed Power Conference, (1976).
The Second IEEE International Pulsed Power Conferncee, (1979).
The 13th Modulator Symposium (1978).
The 14th Modulator Symposium (1980).
The NSWC Pulsed Power Systems Workshop (1976).

(12) Dr. Kristiansen is organizing a pulsed power lecture series for the USAF with support from AFWL, AFOSR, and AFAPL.

(13) Dr. Kristiansen has also worked as a consultant on pulsed power and plasma physics problems to LASL from 1974 to the present time.

(14) Dr's. Kunhardt (TTU), Kristiansen (TTU) and Guenther (AFWL) co-suthored one paper on electron beam triggering of spark gaps at the 3rd Electron/Ion Beam Conference in Novosibirsk, USSR (1979) and one paper on the same topic at the 2nd IEEE Pulsed Power Conference (1979). This paper is being rewritten and submitted for journal publication. The same authors also co-authored a paper on spark gap inductance at the 2nd IEEE Pulsed Power Conference.

(15) Dr's. Kristiansen (TTU), Hatfield (TTU) and Guenther (AFWL) co-authored papers on laser triggering of spark gaps at the 13th International Conference on Phenomena in Ionized Gases (1979) and at the 2nd IEEE International Pulsed Power Conference (1979). This paper is being rewritten and submitted for journal publication.

(16) Dr's. Kristiansen (TTU) and Guenther (AFWL) are co-guest editors on a forthcoming special issue on switching for the IEEE Transactions on Plasma Science.

(17) Dr. Kristiansen served as a consultant to NASA on the space shuttle plasma physics program (1979).

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1. E. Kunhardt and M. Kristiansen - Annual Report No. 2, Grant No. AFOSR 76-3124.

2. "Electron Beam Initiated Spark Gap Breakdown", 1979 IEEE International Conference on Plasma Science', Montreal, Quebec, Canada, June 4-6, 1979, K. McDonald, M. Newton, E.E. Kunhardt, M. Kristiansen and M.O. Hagler.

3. "Simulation of Inductive and Electromagnetic Effects Associated with Single and Multichannel Triggered Spark Gaps", 2nd IEEE International Pulsed Power Conference, Lubbock, Texas, June 12-14, 1979, S. Levinson, E.E. Kunhardt, M. Kristiansen, and A.H. Guenther.

4. "An Electron-Beam-Triggered Spark Gap", 2nd IEEE International Pulsed Power Conference, Lubbock, Texas, June 12-14, 1979, K. McDonald, M. Newton, E.E. Kunhardt, M. Kristiansen and A.H. Guenther.

5. "Applications of Electron Beams for Precise Switching of High Voltages, 3rd International Topical Conference on High Power Electron and Ion Beam Research and Technology, Novosibirsk, USSR, July 3-6, 1979, M. Newton, K. McDonald, E.E. Kunhardt, M. Kristiansen and A. H. Guenther.